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ROTATION CHARACTERISTICS OF THE Fe XIV (5303 Å) SOLAR CORONA

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ABSTRACT

Synoptic photoelectric observations of the coronal Fe XIV line at 5303 Å have been analyzed to reveal the rotational behavior of the solar corona as detected in that line. The data used are measurements made with the Sacramento Peak 40 cm coronagraph of the intensity at 5303 Å observed at a radius of 1.15 $R_\odot$ between 1973 and 1985. A correlation analysis shows that over this epoch, the average synodic rotation period for a band from 30N to 30S was 27.52 days. Examination of the average synodic rotation period as a function of latitude for this interval shows that, as is the case for the white-light corona, on average the Fe XIV corona rotates more rigidly than do features in the photosphere or chromosphere. The yearly average synodic periods vary slightly about the overall mean in a fashion which differs somewhat from the (probably cyclic) variation reported for the white-light corona; slower rotation than the mean is seen only in the ascending phase of the activity cycle. Although the lifetimes for features in the Fe XIV corona are slightly less than those for the electron corona, overall, their rotation properties are more similar to the white-light corona than to those of active regions on the Sun with which they are generally thought to be associated. However, there appears to be a significant and time varying component which shows differential rotation. This component appears during cycle 21 at high ($\geq 60°$) latitudes in the late ascending phase and moves toward the equator. As the cycle progresses, this component becomes indistinguishable from faster rotating features near the equator and the effect is to produce a net differential rotation which is intermediate between that of the photosphere and that of the white-light corona. The observations appear to be consistent with the interpretation that the Fe XIV coronal signal arises from the effects of local heating on the large-scale density structure of the corona.

Subject headings: Sun: activity — Sun: corona — Sun: rotation

I. INTRODUCTION

Emission-line measurements of the solar corona were amongst the earliest means by which the corona was observed outside eclipse (Lyot 1944). Today, together with a large body of white-light observations of the corona made from the ground (Fisher *et al.* 1981) and from Earth orbit (Gosling *et al.* 1974), the emission line data remain most useful for the derivation of quantitative data on the corona. Of the three most easily observed emission lines, [the (red) Fe X λ6374, (green) Fe XIV λ5303, and (yellow) Ca XV λ5964], the data on the Fe XIV line have been most exploited. This is in part because it is present in easily observable intensities more extensively than the others, and in part because its wavelength was most suited to the early photographic recording techniques. As a result, the Fe XIV data form the basis of many early and continuing studies of the corona.

Phenomenologically, Fe XIV observations have been used to examine the large-scale structure and evolution of the solar corona and have been related to various other phenomena on the Sun (Billings 1966). Similarly, the bright emission has been associated with all forms of activity, both in detailed associations (Dunn 1971; Zirker 1971; Altrock 1985 [CMEs]) and in larger scale more global associations (Bretz and Billings 1959; Sykora 1971, 1980). Not only are close associations demonstrated with individual features of the chromosphere, but the global distribution varies in time in a fashion reminiscent of other forms of activity. Thus one component of the Fe XIV traces out a pattern in the corona closely related to the various manifestations of activity displayed in the chromosphere. In contrast, the Ca XV line is found only to be associated with the most intense solar activity, and as a result is found only over large highly active regions characteristic of the maximum of the activity cycle.

In fact, the Fe XIV line emission arises in coronal material with temperatures of about 1.8×10^6 K (Jordan 1969). This temperature is characteristic of most of the corona outside of the coronal holes. Thus, Fe XIV emission is ubiquitous over the entire solar activity cycle. In addition, temperatures of 1.8×10^6 K are also found over active regions, and Fe XIV reaches its highest intensity there. It is thus ideally suited to a study of both the active and quiet coronae.

Moreover, since the emission is proportional directly to some function of the temperature, but to the square of the density, the 5303 Å data provide a particularly sensitive density diagnostic. This was utilized by Waldmeier (1957) in his discovery of what we now refer to as coronal holes and has been further exploited to map coronal holes by Fisher and Musman (1975), Letfus, Kulcar, and Sykora (1980), and Altrock and Gilliam (1986).

Thus the Fe XIV data provide a tracer for magnetic field

[1] The High Altitude Observatory is a division of the National Center for Atmospheric Research, which is sponsored by the National Science Foundation.

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structures both in global scale features which are predominantly coronal, and in the smaller scale chromospheric manifestations of activity associated with active regions. This suggests that the record of the Fe XIV line observations can be viewed in a sense as a synthesis of medium scale chromospheric and semiglobal coronal properties. However, the overall relationship of regions which are bright in 5303 Å to other solar coronal structures has never fully been examined. Thus, the Fe XIV line data may provide a link between the active regions of the chromosphere and the large-scale structure of the corona. In particular, the interaction between these scales is of special interest.

An additional interest derives from the fact that as an example of coronal emission from a largely collisionally dominated plasma, the Fe XIV provides us with a different perspective on coronal properties from any which could be derived from observation of the coronal density alone. This is particularly important because it is through the coronal emission, rather than merely the density structure, that coronae on other stars can be most easily detected. The Fe XIV corona can thus provide us with an understanding of the global behavior of the solar emission corona in relation to other solar phenomena which may therefore help us to interpret observations of other stars.

In this study, we examine the rotational characteristics of the emission line corona as revealed by the Fe XIV data. Although the use of emission-line data has been criticized for the determination of rotation properties of the corona (Newkirk 1967), it has in fact yielded valuable results. In this paper, we analyze the photoelectric measurements made in the Sacramento Peak Observatory (SPO) coronal photometry program (Altrock, Fisher, and Sime 1985) made over the last solar cycle. This provides an opportunity to extend the results of Antonucci and Svalgaard (1974), who studied the rotation of the Fe XIV corona in the period 1947–1970, into another solar cycle using a uniform data set of photoelectric observations. The method is the same as that used for the examination of the rotation of the white-light corona by Fisher and Sime (1984). Section II outlines the method, §§ III and IV present the results, and § V contains a discussion of the present results in the context of previous measurements.

II. OBSERVATIONS AND DATA REDUCTION

The coronal photometry program at Sacramento Peak Observatory (SPO) was begun in 1973 and continues to data. It provides an extended, almost daily, uniform set of photoelectric observations of the corona which can be used to derive a long-term description of the morphology and evolution of the solar emission corona. Together with information on the global structure of the corona, it has also yielded observations of many specific features of the emission line corona (Fisher and Musman 1975) and allowed interpretation of physical conditions within the corona (Fisher 1978). Three of the forbidden coronal visible wavelength emission lines have been studied, Fe X λ6374, Fe XIV λ5303, and Ca XV λ5964 (Sime, Fisher, and Altrock 1985), but in this study, we consider only the observations made during this program in the Fe XIV line: the coronal green line. An overview of the distribution and evolution of the Fe XIV corona over the last solar cycle can be obtained from the compilation of the synoptic maps made from these data by Altrock *et al.* (1987) and from the interpretative study by Altrock (1988).

The instrument and its operation have been described in some detail by Fisher (1973) and Smartt (1982). It consists of a photoelectric photometer operating at the coudé feed of the 40 cm coronagraph at the National Solar Observatory/Sacramento Peak. A mica filter with full width at half-maximum (FWHM) of 0.65 Å is presently used to isolate the Fe XIV line at 5303 Å, but up until 1983 January 4, a birefringent filter of FWHM 0.58 Å was used. A piezoelectric modulator is used to chop between the central bandpass and the nearby continuum in order to remove the contribution of the continuum at this wavelength.

The daily operation comprises a series of scans in position angle at one of a selection of heights above the limb. These heights are usually 0.15 $R_\odot$ and 0.35 $R_\odot$ above the limb with an additional scan made at 0.25, 0.45, or 0.55 $R_\odot$ depending on observing conditions and the general level of coronal activity. Data are gathered at points separated by 3° in position angle and a complete scan in position angle takes approximately 5 minutes. The data are collected on magnetic tape for later analysis. Control of the instrument and of the data collection was handled initially by a DEC PDP 11-10 computer, and subsequently (after 1982 August 31) by a PE 3220.

For the present study, we use the almost daily east limb scans taken at a radius of 1.15 $R_\odot$ from Sun center. After quality assurance and artifact removal, the data are collected on magnetic tape for further processing. The contents of these tapes, a record of the coronal brightness at 5303 Å as a function of position angle at a given height above the limb, have then been reformatted to appear similar to the data collected by the High Altitude Observatory's (HAO's) Mk-III K-coronameter on Mauna Loa. This allows easy application of much of the software written to manipulate and analyze the white-light data. Readers who desire more specific information on the observations for any particular day are referred to Altrock and Gilliam (1986).

We have applied an identical analysis to that of Fisher and Sime (1984) in their study of the rotational characteristics of the white-light corona. The data are divided into yearly intervals and then averaged into bands of latitude (each 15° in extent) centered on latitudes 75°, 60°, 45°, 30°, and 15° in each hemisphere, and the solar equator. This was carried out for each year in the interval 1973–1985, except that in the yearly averaging, the data for 1973 and 1974 were combined. The observations did not start until mid-1973, and the observations for 1974 were sparse toward the end, so the combined data set, although referred to here as for 1974, should be viewed as representing the corona in late 1973 and early 1974. Following the practice of Hansen, Hansen, and Loomis (1969) and Fisher and Sime (1984), we use the autocorrelation method for establishing the synodic rotation period for each band of latitude. Use of this method for yearly data sets yields a formal uncertainty of $\sim$0.3 days per rotational period, comparable to the errors in the maximum entropy method. Further, Seagraves and Garcia (1985) have demontrated that the effects on the results derived from this method of typical and inevitable data gaps, due to poor weather or instrument maintenance, bias the result if they occur uniformly in time by, at the most, 0.11 days. Small changes in the instantaneous synodic rotation rate (e.g., due to the ellipticity of Earth's orbit) are lost in the yearly averaging.

In this, as in any analysis using observations gathered over a long time interval, it is important to understand any fluctuations in the quality and precision of the data and their effect on the analysis. Often, the lack of long-term stability in the photometry is a major problem. In the present case, however, we believe the photometric response of the instrument is maintained adequately over periods of about a year, comparable with the lengths of the individual data series used. Specifically, our use of the autocorrelation technique with lags of a few tens of days, on data with long-term trends removed, limits the length of time over which given photometric precision is required to about 1 yr, and daily checks indicate that this requirement is well met. One systematic error that has been identified is an offset of position angle between the east and west limb data of approximately 6° in altitude. This will have the effect of assigning latitude incorrectly by a small amount, but since we use only observations made on the east limb, it should have no other effect on the results.

The data series for each latitude band had any significant long term trend removed from it before calculations of the autocorrelation function (ACF). As in Fisher and Sime (1984), the autocorrelation at lag l (in days) for the band at latitude ϕ is defined as

$$\rho_\phi(l) = \frac{\sum_{i=1}^{N}(B_{i,\phi} - \bar{B}_\phi)(B_{i+l,\phi} - \bar{B}_\phi)}{[\sum_{i=1}^{N}(B_{i,\phi} - \bar{B}_\phi)^2 \sum_{i=1}^{N}(B_{i+l,\phi} - \bar{B}_\phi)^2]^{1/2}} ,$$

where

$$\bar{B}_\phi = \frac{1}{N}\sum_{i=1}^{N} B_{i,\phi}$$

with N the length of the data series (365 days) and B the brightness of the corona in the instrument line bandpass in units of millionths of the brightness of the center of the solar disk. The timelike coordinate l is referred to as the lag.

After the autocorrelation functions were estimated for l between 0 and 90, the peak of the first positive maximum between $l = 25$ and 35 was identified, and the center of mass of the function in that region was estimated. Following Fisher and Sime (1984) and Hansen, Hansen, and Loomis (1969) this was taken to be the estimate of the synodic rotation period. The underlying assumption in such an interpretation is that the coronal structures persist for at least 27 days and give rise to a local maximum in the ACF as they appear across the east limb on successive solar rotations.

The autocorrelation functions so generated are similar in appearance to those calculated for the white light data by Fisher and Sime, and in particular showed a qualitatively similar evolution in their appearance throughout the progress of the solar cycle. Not only did the value of the autocorrelation at ~1 rotation lag (i.e., 27 days) change with time, but the lag at which this peak occurred also changed.

III. ROTATION OF THE Fe XIV CORONA

From the estimates for the location of the lag in the ACF representing one rotation, it is possible to derive a yearly average synodic rotation period for each of the 15° wide latitude bins used in this study. The values for the Fe XIV observations are presented in Table 1, and can be summed to lead to an overall average synodic rotation period (averaged over both time and latitude) for the Fe XIV corona of 27.52 ± 0.42 days in the 1974–1985 epoch. The variations displayed by this quantity can be explored by examining the rows and columns of this table. For example, Figure 1 shows the time-averaged synodic rotation period separately for each of the latitude bands from +75° to −75°. The year-to-year variation measured is indicated by the bars drawn at each point which represent the standard deviations in the means. Note that the curve is relatively flat: the averaged synodic rotation period values vary only slightly with latitude, from just below 27 days per rotation period at the equator to just more than 28 days at 45° latitude. The value at the equator is the lowest of the set, while the longest periods are apparently associated with the 45° latitude bins in both hemispheres, and the 60° bin in the south. Overall, however, this variation of rotation rates with latitude is significantly less than the variation frequently reported for photospheric and chromospheric tracers (e.g., Howard *et al.* 1983). Rather, the relative rigidity displayed by the emission-line corona is comparable to that reported in studies of the white-light coronal rotation rate (Fisher and Sime 1984). However, the equatorial synodic period, 26.83 days, is slightly lower than that reported for the white-light coronal rotation in the epoch 1964–1984 which was 27.17 days. For the subset of white-light estimates from all latitudes for the same years as the white-light data are available (1974–1985), the rate is 27.51 ± 0.53. This set excludes 1979, for which no K-corona observations are available, and shows again a slight, if marginally significant, difference between the periods measured using the Fe XIV and white light observations.

Temporal variations can also be identified in the values of the rotation period in Table 1. The character of these variations is indicated in Figure 2, which displays the yearly average

TABLE 1

Fe XIV CORONAL SYNODIC ROTATION PERIODS

Year	Latitude Bin −87°	−60°	−45	−30°	−15°	0°	15	30°	45	60°	75
1974[a]	26.14	27.87	27.58	26.56	25.00	27.35	20.22	27.15	28.20	26.67	29.07
1975	25.88	28.01	27.92	27.79	27.06	26.78	27.49	28.33	27.41	27.74	25.85
1976	26.69	28.49	28.37	27.87	26.73	26.80	26.89	28.28	22.43	27.81	26.21
1977	26.43	29.21	29.89	27.93	27.44	26.32	26.93	28.29	29.07	29.97	28.29
1978	28.40	28.34	28.80	27.69	27.95	27.11	26.68	27.40	28.73	27.29	26.69
1979	30.11	29.63	28.49	28.08	28.46	26.72	27.10	27.79	28.53	28.94	28.52
1980	25.34	28.25	28.91	27.50	27.28	26.47	27.66	27.88	27.57	27.36	28.62
1981	28.18	27.80	28.04	27.45	26.77	26.83	26.88	27.15	28.95	27.45	28.05
1982	28.08	27.69	27.84	27.65	26.87	26.76	27.42	27.68	27.29	27.05	28.38
1983	28.43	27.86	27.41	27.16	28.59	27.87	26.80	26.82	27.07	27.08	26.76
1984	27.06	27.00	26.78	26.41	27.32	26.12	26.83	26.93	27.36	27.48	26.88
1985	27.37	27.13	27.38	27.14	26.90	26.69	27.02	27.07	27.39	27.35	26.97

[a] Data labeled 1974 are from late 1973 and early 1974.

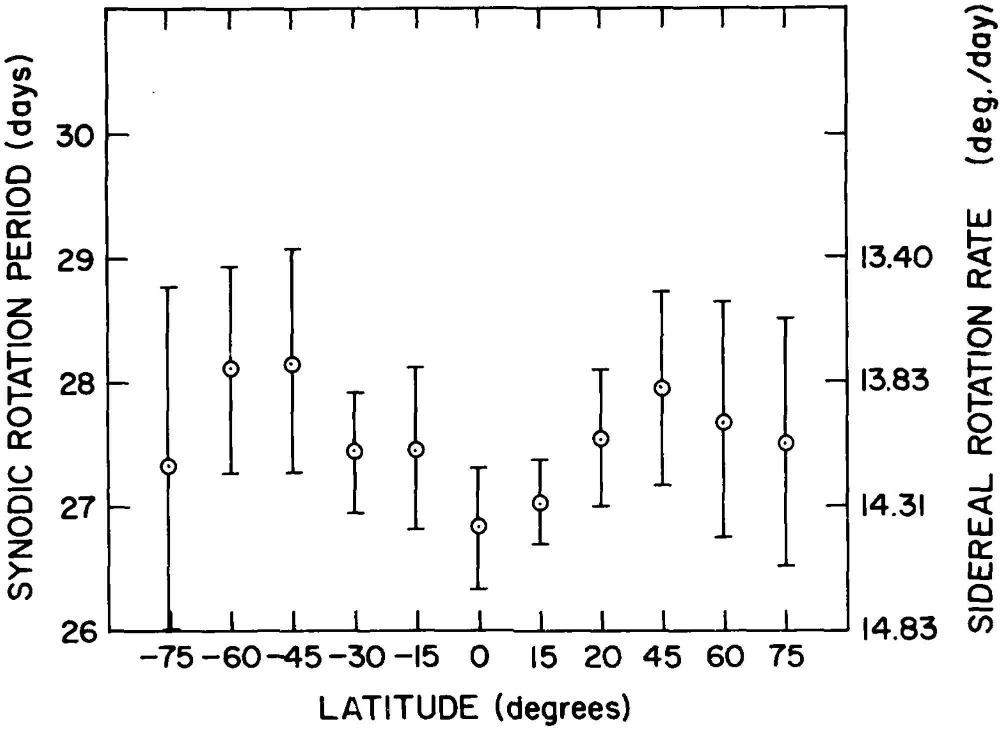

FIG. 1.—The averaged synodic rotation period for the Fe XIV corona (1973–1985) observed at 1.15 $R_{\odot}$ shown as a function of latitude (15° bins). The indicated error bars depict one standard deviation in the mean of each latitude bin. The corresponding values for the sidereal rotation rate are given on the right-hand ordinate.

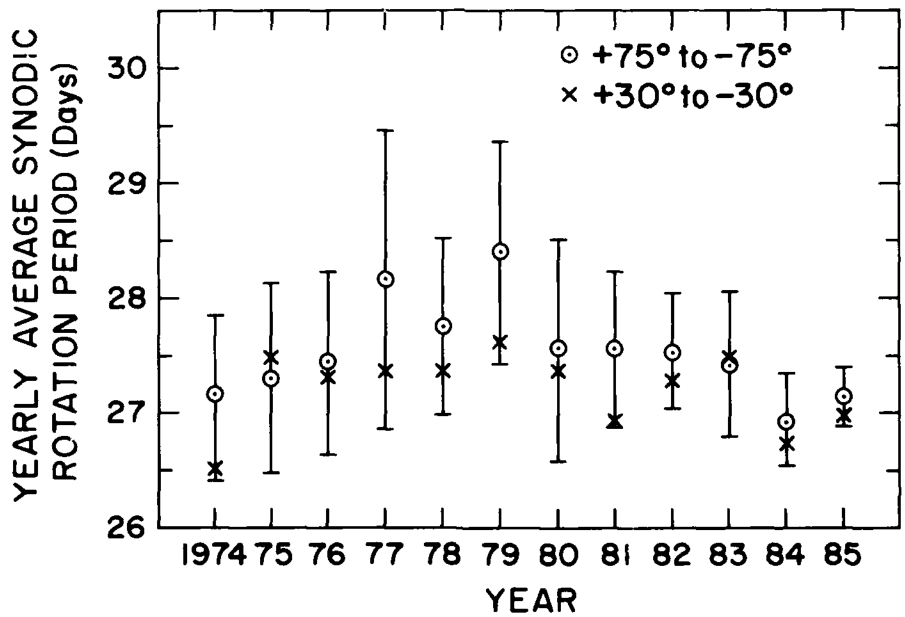

FIG. 2.—The yearly average synodic rotation period for the Fe XIV corona shown as a function of year for the interval 1974–1985. The data are shown both averaged over all latitude bins ($\pm 75°$) for each year, and for averages over the interval $\pm 30°$ latitude (*crosses*). The indicated error bars depict one standard deviation in the mean of the $\pm 75°$ data for the year.

synodic rotation period as a function of time for the interval 1974 to 1985. The data are shown both for the average over all latitudes, and for the average over the band $\pm 30°$. In this figure, the error bars at each point indicate the variance in the yearly average over all latitudes. It can be seen in Figure 2 that the yearly averages vary modestly, showing a difference of about 1 day per rotation period between the highest and lowest values. These variations can be characterized over the last cycle as indicating higher values in the late ascending phase of the last solar cycle and lower values near solar minimum. Comparison of the results for the two latitude bands indicates that the data for the equatorial band ($\pm 30°$) show both a reduced period and variation in period. The values indicate that the results from the wider latitude range show longer periods in 1977, 1978, and 1979, but also emphasize the generally fairly uniform value for the rotation period during this epoch with a significant deviation from that showing up only in the late 1970's, i.e., just before solar maximum. Overall, the periods measured for the latitude range of $\pm 30°$ are shorter giving an average value of 27.05 ± 0.44 days compared with the period for all latitudes of 27.52 ± 0.42 days. Similarly, the values for the equatorial belt display the reduction of the period, i.e., an increase in the rotation rate, in 1974, and again in 1984 and 1985.

For the wider latitude range the average synodic rotation period is marginally longer, there are statistically significant departures from the mean rate for both bands, but more so for the $\pm 75°$ band. We take this as an indication of a significant, but more slowly rotating, contribution from Fe XIV emission regions at high latitude which varies with time. Also, the variation in time of the periods is much harder to identify, and it seems more plausible that any time variation present is apparent only in a short interval near solar minimum, when the measured period is somewhat reduced. The bulk of these temporal variations in the overall Fe XIV signal thus seems to be associated with the higher latitudes.

The presence of such an effect can be more clearly evaluated by examination of the rotation rate for each latitude with time as displayed in Figure 3. Here the yearly synodic rotation period average for several latitudes is plotted as a function of time over the interval of this study. For clarity, the results for only three latitudes (60°, 30°, and 0°) are shown, separated by

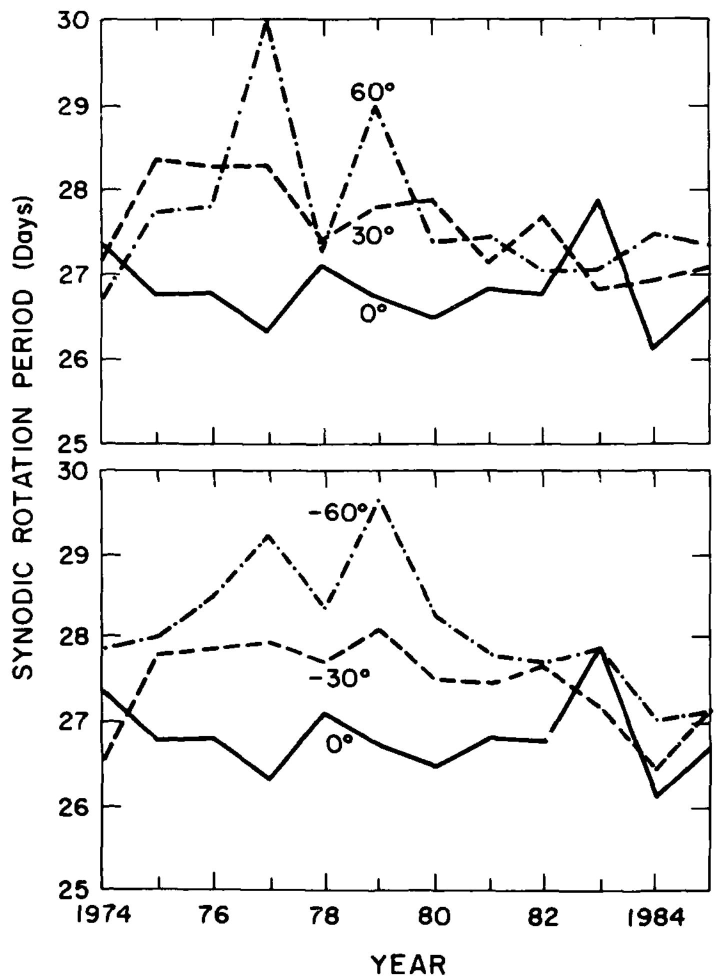

FIG. 3.—The yearly average synodic rotation period for the Fe XIV corona, in days, shown as a function of time for selected latitudes. Data are shown for the latitudes 60 (*dot-dash*), 30° (*dash*), and 0° (*continuous*).

hemisphere. In this figure, the almost constant value of the equatorial rotation rate is seen in the curve for 0° latitude, as is the similar constancy (with a slightly longer period) of the mid latitude data (30°). In contrast, the data from the 60° latitude band show a generally higher value with marked excursions in the years 1977–1979. Thus, as mentioned above, the indication is that the variation seen in the averaged curves arises principally from the effects of these high-latitude regions. The role of the high latitudes will be discussed more in § V.

IV. STRUCTURE LIFETIMES

From the calculated autocorrelation functions, it is also possible to estimate the persistence of the coronal structures observed in the Fe XIV data. The reduction in amplitude from unity of the peak in the autocorrelation at a lag of one rotation period is due to the evolution of the coronal structure over that interval of about 27 days. By interpreting the ACF as being the product of a periodic function which arises from the rotation of a static structure, and an exponential which represents the decorrelation due to evolution of the structure, the ACF can be parameterized to yield a quantity τ, which satisfies the relation

$$\tau = -P_{\text{corona}}/\ln \rho(P_{\text{corona}}) ,$$

where τ is in days, P_{corona} is the appropriate rotation period, and ρ is defined as in § II above. Quite simply, τ is the $1/e$-folding time of the coronal autocovariance signal and is referred to here as the correlation lifetime of the Fe XIV corona. Thus in the case where the coronal structures seen in the Fe XIV emission are stable and long-lived we expect τ to be large, while coronal structures which are not so long-lived will lead to values of τ which are small. An analogous measure of the persistence of coronal structures was used by Fisher and Sime (1984) for their study of the K-coronal rotation.

The long-term behavior in time of this parameter τ throughout our study is shown in Figure 4. This plot displays yearly average values of τ calculated for two ranges of latitude, $\pm 30°$ and $\pm 60°$. The data from the highest latitudes (75°) are omitted since the estimates are very poor. An important point is that the values for τ are all above about 30 days. Thus the underlying assumption in this analysis, that the coronal signal is stationary enough to permit the use of an autocorrelation analysis, at least out to lags of about 30 days, is valid. In general, there is not much year-to-year variation, and the most striking feature is a trend observed at the end of the epoch under study. As expected, the temporal scales tend to be small near solar maximum, but they are just as small at other times. Except for the data from 1984 and 1985, all other points are within a factor of 2 of the value for 1980. Also, there is little sign of any variations which might be attributed to cyclic effects in phase with the solar activity cycle. Specifically, the observations from the times r ır 1974 do not resemble the results for 1985. The observations for 1974 included very low

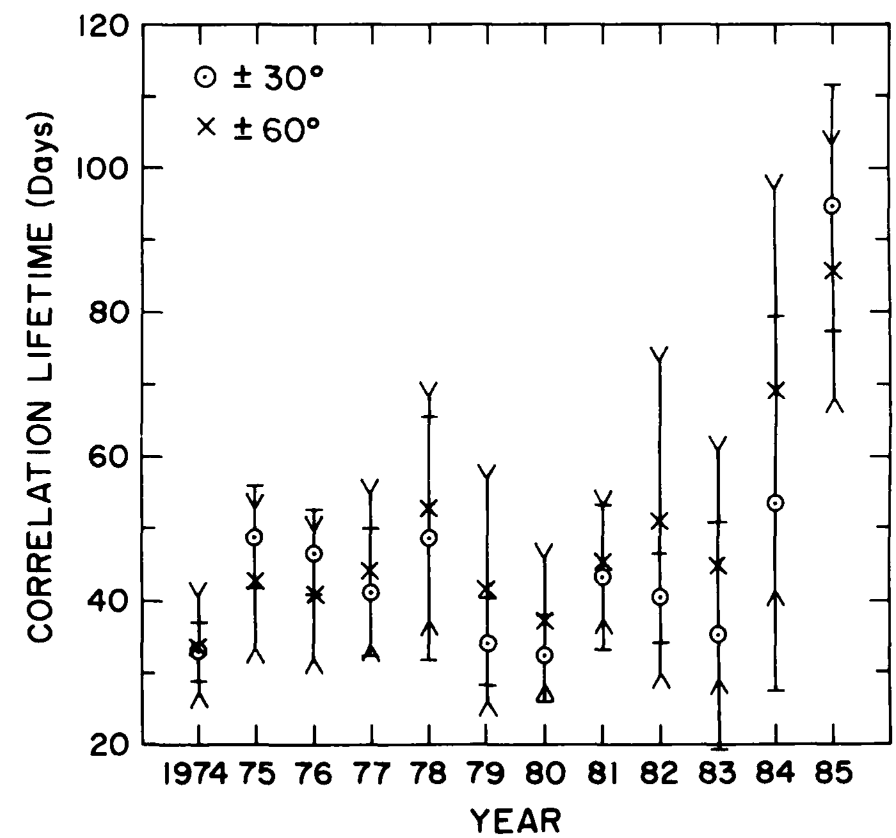

FIG. 4.—Temporal variations of the Fe XIV corona: Correlation lifetime τ (defined in the text) for the 5303 Å data taken at 1.15 $R_{\odot}$ plotted as a function of year in the interval 1974–1985. The ⊙ symbols are for data within the latitude interval ±30°, while the × symbols are for data within the band ±60°. The error bars indicate half a standard deviation in the mean for each year.

values for the intensity of the Fe XIV corona (Altrock *et al.* 1987), so may suffer from problems associated with low-signal-to-noise ratio (although the error bars shown are relatively small), but comparable signal levels are present in the 1985 data. Also, the general level of activity in 1974 was much less than in 1985, suggesting that different global properties obtained for the Sun and corona.

Comparison of the two latitude bands, however, reveals some differences. Although the general character of the curves is similar, the data for the latitude band $\pm 60°$ show slightly larger variances. The values of τ for the $\pm 30°$ and $\pm 60°$ bands do not differ significantly, although inspection indicates the tendency for the estimates $\pm 60°$ band to be slightly higher near and just after the maximum of the activity cycle. These effects are slight, the values are still comparable with those for the lower latitudes, and there is little significant difference in lifetimes in the late ascending phase of the solar cycle, when we might expect the evolution of the corona to be at its most rapid.

These data again point to the variability that the high latitude contribution to the yearly averages introduces. To examine this, we have plotted in Figure 5 the average values of τ as a function of latitude. Again, the variation in τ is not great—a factor of $\lesssim 2$ at best—and the shortest time scales are found in the active region band, near the equator, while the areas at high latitudes, $>45°$, show longer time scales, although the differences are of marginal significance. Although features may appear at high latitude near the maximum of the activity cycle with slightly longer than average lifetimes, they do not alter the overall result which is dominated by the short-lived regions near the equator.

V. COMPARISON WITH K-CORONAL OBSERVATIONS

It has been shown that on average over an interval of about one solar cycle (11 yr) the large-scale solar coronal structure seen in the Fe XIV emission rotates with an overall average rotation period of 27.52 ± 0.42 days, and that on average it tends to rotate with little difference in rate as a function of latitude. Rather than displaying the rotational characteristics of the chromosphere, the Fe XIV corona rotates rather like the white-light corona. The similarities are marked; the overall average rotation rate was 27.39 for the Fe XIV data between 1974 and 1985, while for the white-light observations, Fisher and Sime (1984) reported an average (for the epoch 1965–1983) of 27.23 days. For the period when both green line and K-coronal data are available (extended to include 1984 and 1985), the white-light rotation period was 27.51 days. Similarly, the relative rigidity of the corona seen at 5303 Å is comparable with that reported by Fisher and Sime (1984) for the white-light data, and as such is markedly different from the differential rotation typically seen in other tracers of solar rotation.

Using the data for years in common, it can be shown that the two sets of rotation period estimates are not statistically independent (at the 97% confidence level). As a result it is tempting to infer that the organization of structures detected in the white-light coronal observations and that seen in the emission line observations are not physically independent. This is to be expected since the Fe XIV signal is proportional to $\int n_e^2 F(T) dl$, where $F(T)$ is the dependence of the Fe XIV emission on temperature, while the white-light signal is proportional to $\int n_e dl$. The distribution of electron density thus underlies the observed brightness distributions in both of the data sets. The

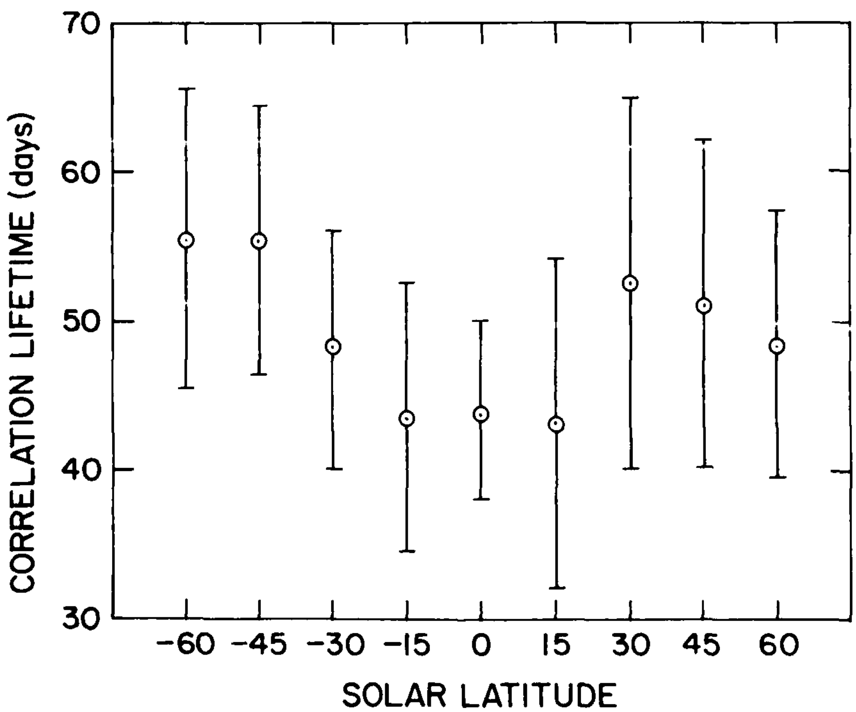

FIG. 5.—Variation of the Fe XIV coronal lifetime with latitude: Correlation lifetime τ averaged over the interval 1974–1985 is shown as a function of solar latitude in the range 60° N to 60° S. The error bars indicate one standard deviation in the mean estimated for each latitude bin.

similarities in the two sets of observations reflect the properties of the density structure of the corona. To the extent that differences can be established between the two, these must reflect the effect of other properties of the corona, presumably the temperature distribution effective on or within this structure. It is also important to realize that the Fe XIV observations were made at a height of 0.15 $R_{\odot}$ above the limb, and that the K-coronal data were gathered at a height of 0.3 or 0.5 $R_{\odot}$. The Fe XIV data are thus more likely to be influenced by the presence of active regions more than the K-coronal data are, and will also represent structures controlled by smaller scale magnetic fields.

The temporal variations of the rotation properties measured in white light and in the Fe XIV line show some significant differences. Fisher and Sime (1984) demonstrated a (probably cyclic) modulation of the rotation period of the K-corona with an amplitude of about 1.4 days (peak-to-peak) such that the maximum period occurred a few years before the maximum of the sunspot number cycle. The variation was seen both in the data from all latitudes, and in the observations of the equatorial band ($\pm 30°$) alone. In the case of the Fe XIV observations, almost the same long-term modulation can be identified, at least in the data from all latitudes. Although this modulation may be similar to other apparently cyclic changes, because the Fe XIV observations are so short, it is hard from the present data alone to claim the presence of a cyclic effect. However, the increase in period occurs a little earlier than for the K-coronal data, in fact during 1977, 1978, and 1979, and the period has returned to its average value by the time of the sunspot number maximum in 1980. After staying almost constant for some years, it decreases at the approach of sunspot minimum. However, with such a short data series, such variations could be spurious. In the equatorial band data, the modulation is less pronounced and can be identified principally as a decrease in period around solar minimum. The contrast between these two coronal rotation measures may be related to the observation by Gilman and Howard (1984) of the cyclic modulation of the rotation rate of sunspots. They reported that equatorial sunspots ($\pm 15°$) showed a cyclic maximum in rotation rate (minimum period), on average some 0–3 yr after the minimum of the sunspot number. This was both true for observations over the interval 1921–1982, and specifically for the epoch 1967–1982.

A plausible explanation of the Fe XIV results may be that the rotation period maximum reflects the behavior of the large-scale coronal density structure as detected with the K-coronal observations, while this modulation is suppressed in the equatorial bands by the influence of magnetic field structure intimately associated with sunspots which are undergoing angular acceleration at this time. This is perhaps not very likely, since Fe XIV features at high latitudes seem to be important at this time, and since the amplitude of the sunspot rotation rate modulation is considerably smaller (25%) than those of the coronal rotation rates; however, uncertainties may indeed allow such an effect. If one accepts the interpretation that these modulations are related and their phases relative to one another reflect the propagation of some effect from one scale to another, e.g., sunspots to Fe XIV corona to K-corona, it is hard to explain the delays in terms of any known process which might take place above the photosphere. Any such interaction must be rooted deep in the Sun.

The closest similarity between the emission line and white-light data sets is the overall rotation period average. The details of this are best revealed by inspection of the relationship between the yearly averages of the two measures. Figure 6 shows the values for the period in the Fe XIV data, P_{Fe}, plotted against the values of the period in the K-corona data, P_K for the years during which observations were available for both. The average values of P_K and P_{Fe} are of course similar, but times of shorter than average Fe XIV period seem to correspond to times when the Fe XIV period is greater than that for the K-corona (i.e., the K-corona is rotating faster); and vice versa. A straight line fit to the observations in Figure 6 yields the relation $P_{Fe} = 13.81 + 0.496P_K$, as indicated in the figure.

The distinction of the two coronal signals can be investigated further by examining the quantity $\Delta P = (P_{Fe} - P_K)$, the difference in measured Fe XIV and white-light rotation period as shown as a function of latitude in Figure 7. The indication from this plot is that the equatorial and low-latitude values of this difference are generally negative, while the values at higher latitudes become positive. Note, however, that this result is marginal in the presence of uncertainties of ± 0.3 days in the period estimates. If this effect is real, it suggests that the Fe XIV period is smaller near the equator than the white light period, while the situation tends to be reversed at higher latitude where the K-coronal period is smaller. However, the positive values seen at higher latitudes tend to be smaller in absolute value than the results for the lower latitudes. Given the fairly rigid behavior of the K-corona, this suggests that a significant component of the emission line corona may actually display differential rotation, in the sense that the equatorial features rotate somewhat faster than the K-corona at these latitudes and possibly rotating more slowly than the K-corona at higher latitudes.

Such an effect can be examined directly using the present data set. Although the long-term average rotation period shows little dependence on latitude (Fig. 1), some variation is apparent in the averages and is also indicated by the dispersion in these means. This suggestion of possible differential rotation effects in these data can be investigated by examining the estimated period as a function of latitude, year by year throughout the interval. The results are shown in Figure 8, where, for clarity, only a selection of years has been shown. For each year represented, the average rotation period is given for each of the latitude bands. The effect is dramatic in this presentation, but the displayed rates are of course consistent with the dispersion indicated in Figure 1. Here, the individual curves vary significantly indicating the presence of a differential rotation effect which is quite varied over time. In Figure 8, 1985 shows a relatively flat trace for the behavior of rotation period with latitude, with only approximately half a day's difference in period between equatorial and high-latitude regions. The curves for 1984 and 1985 are both rather flat, and within the uncertainties appropriate to this study, could be adequately approximated by a straight line, indicating the absence of any variation in rotation rate with latitude in the Fe XIV corona. On the other hand, in 1977, a strong dependence on latitude is present, leading to a difference in period of up to 3 days between the equatorial region and the high latitudes (60°). Intermediate between these two extremes is 1980, the interval of the maximum of the activity cycle. Just as 1980 is not particularly conspicuous in any of the observations reported here, it seems that it is rather close to average behavior with respect to the differential rotation. The data for 1979 and 1980 (solar maximum) are intermediate in the extent to which the differential rotation is displayed, with the indication of a progression

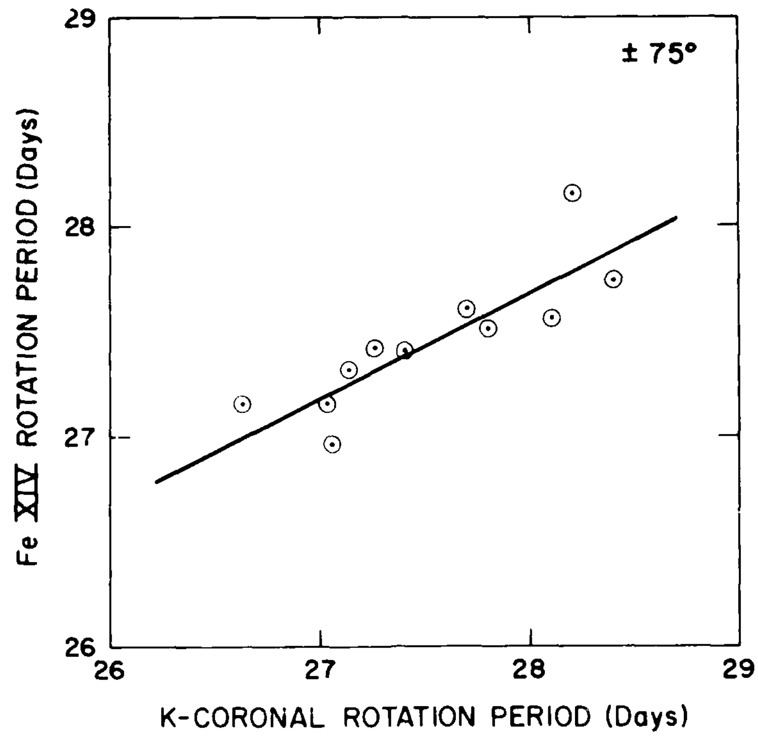

FIG. 6. Comparison of rotation identified from white-light and green line observations. Synodic rotation periods estimated by Fisher and Sime (1984a) from the K-coronameter data are plotted vs. the periods estimated from the Fe XIV data for the interval 1974–1985. There are no white light observations for 1979.

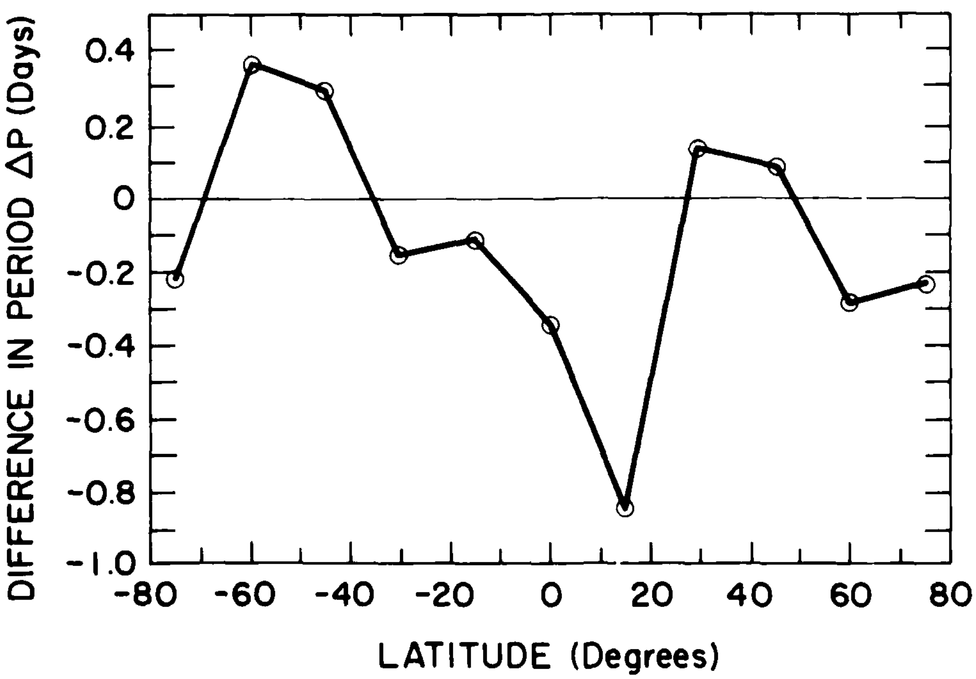

FIG. 7. The difference between rotation periods measured from the white-light (K) and the Fe XIV data. The value $\Delta P = (P_{Fe} - P_K)$ is plotted as a function of latitude. No data are shown for 1979.

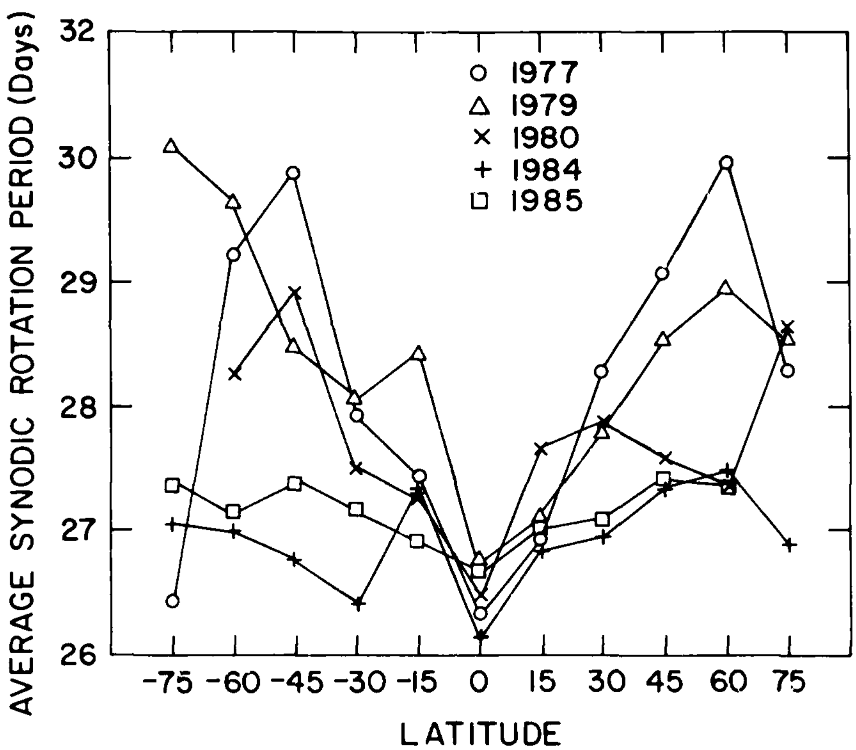

FIG. 8 Comparison of the coronal Fe XIV synodic rotation dependence on latitude for several years. Data are shown for 1977 (*circles*), 1979 (*triangles*), 1980 (*crosses*), 1984 (*plusses*), and 1985 (*squares*).

from the marked effect in 1977 to the rigid rotation found for 1984. Intermediate years, not shown in Figure 8, also follow this trend and reinforce the notation of a progression. Thus, when viewed 1 yr at a time, the variation of rotation of the Fe XIV corona can change from almost flat (independent of latitude) to quite variable with latitude —tending in these cases to show a differential rotation rate comparable to that of the photosphere and chromosphere. This is a significant departure from the behavior of the corona observed in white light and will be discussed in more detail below. The appearance of slowly rotating features at high latitudes in the interval 1977–1979 is simultaneous with the appearance of a "rush to the poles" phenomenon identified by Hansen *et al.* (1969) and Altrock (1988). In addition, the apparent reduction in high latitude, more slowly rotating features after 1980 probably arises from features also identified by Trellis (1957), Leroy and Noens (1983), and Altrock (1988) in high-latitude activity zones that migrate equatorward in bands which parallel the main migration of midlatitude regions of activity which form the butterfly diagram.

To illustrate the magnitude and variation of this differential rotation effect, we have plotted the synodic rotation rate for the Fe XIV corona against latitude in Figure 9 on the same scale as the measurements of the K-coronal rotation and the results for two other tracers of the solar differential rotation. On this plot are shown the synodic rotation rate estimates of Howard *et al.* (1983) which is derived from the Doppler shifts observed in photospheric material, and the rotation inferred from magnetogram measurements by Snodgrass (1983). Also shown, for completeness, is the overall average rate measured by Fisher and Sime (1984) for the white-light corona, and in each case, the results have been folded about the equator to represent the average (northern and southern hemisphere) behavior with latitude. These are compared with the two years of observations of Fe XIV data, 1977 and 1985, which display the extremes of the differential rotation profiles in Figure 8.

A point to note from this curve is that although the Fe XIV coronal data for 1977 show a significant differential rotation, the effect is markedly less than that shown for the photospheric tracers displayed, showing an amplitude of only about one-half the magnitude of the average effect in the photosphere. Thus even in the case of the most pronounced indication of differential rotation in the Fe XIV data, the effect is intermediate between that of the photospheric tracers and that of the large-scale coronal density structures as indicated by the K-coronal observations.

VI. DISCUSSION

In their study of the K-coronal rotation, Fisher and Sime (1984) noticed that the rigidity of the rotation of various tracers, displayed in a figure similar to Figure 9, was ordered in wavenumber. The rotation measured for the data with the lowest spatial wavenumber, i.e., largest scale, was the most rigid, while the Doppler data, which represented structure on the smallest scale, showed differential rotation. They suggested that the scale sizes of the structures observed might also reflect the depth at which these fields originated and as a result provide some clues as to the rotation of the subphotospheric regions in the Sun. It is interesting to note that this same ordering appears to be preserved in the present data set. The Fe XIV data, referring to higher wavenumber than the K-coronal data but lower than the photospheric tracers, shows a

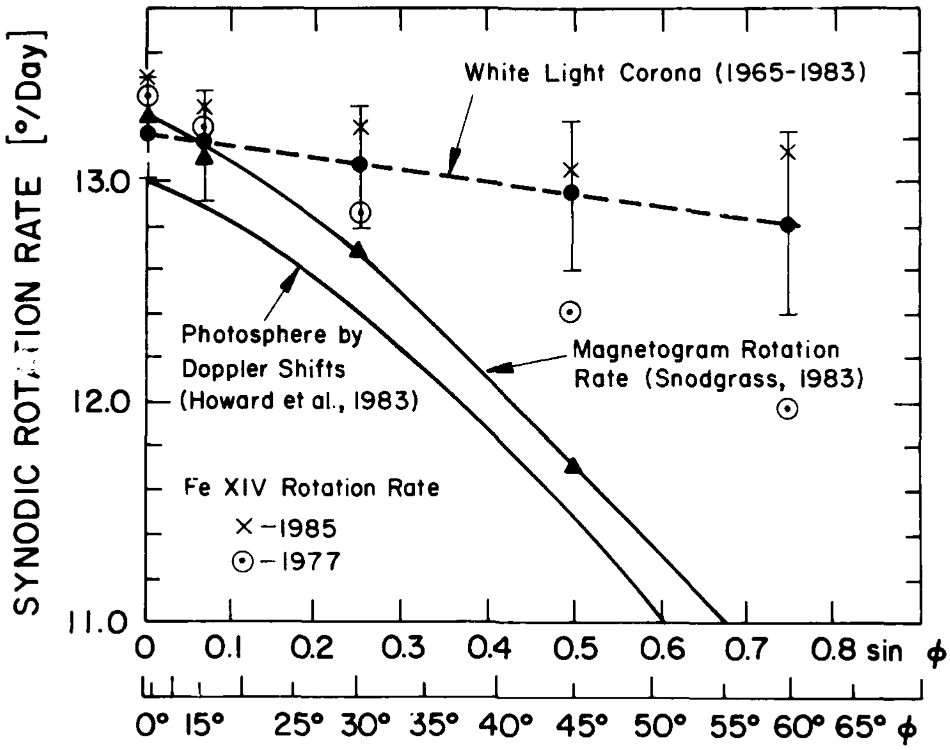

FIG. 9.- Comparison of the estimated coronal Fe XIV synodic rotation periods for 1977 and 1985 with other tracers of solar and coronal rotation

differential rotation effect which is intermediate between the coronal and the photospheric. Further, the time dependence of this effect is in phase with the development of intermediate scale phenomena (chromospheric active regions) which affect the Fe XIV corona. Thus, the variation in time of the differential rotation makes it reasonable to infer that the rotation of the Fe XIV corona is due to the influence of two rotation rates: (1) a near-photospheric rate appropriate to active region rotation and (2) the large-scale K-coronal rate.

Of course, the existence of the differential nature of the rotation of the Fe XIV corona and variations in the amplitude of the effect have previously been reported. Antonucci and Svalgaard (1974) studied the rotation of the Fe XIV corona and identified a temporal variation of the rotation rate in different latitude bands, some epochs even displaying a differential rotation which was the same as that for short-lived photospheric magnetic fields. Utilizing a data set restricted to the interval 1970–1974, Antonucci and Dodero (1977) pursued this question and concluded that the amplitude of the differential rotation varied systematically with sunspot number and inferred that it thus changed with the solar cycle. Specifically, they characterized the results as showing the presence of differential rotation at times of high and decreasing sunspot number and identified the differentially rotating component with the dominance of active regions. Conversely, during intervals of low sunspot number, there was little variation of rotation rate with latitude. Although there are differences in the observations and analysis between the present work and that of Antonucci and Dodero, the results should be qualitatively similar. However, the observations in Figure 8 show a slightly different result. We observe differential rotation to be most pronounced in the 1977–1979 epoch, at the late stage of the ascending phase of the activity cycle, when the values of sunspot number are still increasing. Further, although there is still some detectable differential rotation in the data from 1980, the year of the solar maximum, the effect is much reduced from the previous few years. This somewhat modifies the conclusion from Antonucci and Dodero (1977) that the corona rotates differentially while active regions are prevalent, and suggests it may be during the time of the development of active regions that the differential rotation becomes important.

Indeed, the present results show little qualitative difference from the work of Antonucci *et al.*, indicating rather a quantitative difference, both in the intervals with respect to the nearest solar maximum in which the differential rotation is displayed, and in the extent to which it is displayed. To examine this feature of the observations we have identified those years in which differential rotation is displayed and attempted to quantify the effect by fitting a relation of the form $P_{Fe} = a + b \sin^2 \lambda$, where λ is the heliographic latitude. In each of these cases, but not in the remaining years, the significance of the fit to this relation was better than that to a straight line, justifying our subjective identification of the years with differential rotation. The results of this quantification are shown in Table 2, along with the formal error in the estimate of the coefficient b. Clearly the maximum extent of the differential rotation occurs before 1980, and the effect, although still present, is reduced by the maximum of the cycle.

On the other hand, the present work agrees with the results of Antonucci and Svalgaard (1974) in detecting that the equatorial and low-latitude band rotation rates vary little with time. The variation is at the level of less than a day per rotation at the equator, although somewhat larger at 15°–30° latitudes, and occurs with the largest amplitude in the few years before

TABLE 2

Fit Coefficients for the Latitude Dependence of Synodic Rotation Period

Year	b	$\pm\sigma_b$
1976..........	1.74	0.74
1977..........	4.12	0.78
1978..........	1.30	0.97
1979..........	2.65	0.71
1980..........	1.21	0.88
1981..........	1.58	0.81

the activity cycle maximum. We note also that the rates and amplitudes of the differential effect reported here agree with those reported by Antonucci and coworkers.

In evaluating the importance of the differences between the present results and those published earlier, it should be remembered that individual solar activity cycles can vary considerably. Within the present data set, for example, as shown in Figure 2, there are significant differences between the results from the most recent (1984–1985) and the previous (1976) solar minima. Further, study of the K-coronal data has indicated that the activity cycle delineated by the modulation of sunspot number may not be the most appropriate for considerations of the corona, and that it is very difficult to establish the reality of cyclic effects from the limited data sets available.

In a further investigation of their earlier results, Antonucci and Dodero (1979) were able to organize their data into intervals when the corona was dominated by structures of short or long lifetimes and to demonstrate that the magnitude of the differential rotation varied according to the lifetime of the coronal structures which they observed. Specifically, in reexamining the data from the 1972–1974 epoch, they showed that short-lived structures rotated differentially, while the longer lived features obeyed a rotation law which varied very little with latitude. In the present case, very little variation in the lifetimes of the Fe XIV structures (as measured by the quantity τ; see Fig. 4) can be identified, and in particular it is not possible to partition the data into epochs of lifetimes as distinct as those used by Antonucci and Dodero of 27 and 54 days. To the extent that variation can be identified, no clear difference can be established between intervals when differential rotation can be observed or cannot be observed. Not only are relatively short lifetimes found during periods of marked differential rotation, but they are also present in periods of apparently rigid rotation.

The overall behavior of the persistence measured for the Fe XIV data marks a further difference between the K-coronal observations and the Fe XIV data. As shown in Figure 4, there is not much variation with time within the Fe XIV coronal correlation lifetime observations. The most marked variation is shown in 1985 when the lifetime is largest. More interesting, however, is the absence of any pronounced variation which might be associated with the solar cycle. The value of τ for 1980 (maximum of the activity cycle) is indeed the lowest, but it is not significantly lower than the values for 1975, 1976, and 1977. The tendency is, however, for slightly longer lifetimes to be present in the 1978 data (and again for 1982–1985), but again, the effect is small and given the uncertainties in estimating τ, may not be significant.

This result is quite different from the white light results. The K-coronal signal showed a very strong modulation of the lifetime (τ) as a function of time, with values of 30 days typical near solar maximum, and values of well over 100 days prevalent at time of solar minimum (Fisher and Sime 1984). This behavior is not seen in the emission-line data. The modulation in τ seems less pronounced, and whereas long time scales are measured in the 1984–1985 interval, they are associated with fairly large error bars and do not reflect the behavior seen at the last minimum. The differences are emphasized in Figure 10 where the yearly average lifetimes for the Fe XIV corona are plotted against those for the K-corona for years when there were observations available for both during the interval 1974–1985. Even without the results from 1984 and 1985, the correlation lifetime, τ, for the Fe XIV data seems almost independent of that for the white-light observations. Figure 10 shows no trend; the K-coronal values vary throughout the range 20–100 days, while the values from the Fe XIV observations do not appear to show any correlation with them. Thus overall, the values of τ agree with the K-coronal values only near maximum, but are significantly shorter near the minimum of the cycle. Such a result would be expected to follow if indeed a fundamentally lower value of τ pertains for the Fe XIV corona, and suggests again that the interpretation of the total Fe XIV signal as arising from two components may be valid.

When viewed in detail, and in spite of the statistical similarity shown between the K-coronal rotation rates and that for the Fe XIV corona, there are significant differences between the two. The presence of a temperature dependent term in the expression for the integrated emission line intensity is the most important formal difference in the description of the two signals. We thus conjecture that the data reveal the effect of local heating, by processes associated with active regions, of restricted volumes of the large scale, long lived density structure of the electron corona. If the Fe XIV signal is viewed as revealing the combination of the distribution of local heating centers and the overlying density structure, the properties of the resulting Fe XIV emission signature will resemble a convolution of the properties of the two separate distributions: one coronal and one chromospheric. The rotation properties similarly will reflect a combination of properties of the two. A test of the validity of this conjecture would be to examine whether the reported behavior of the two data sets lends itself to a consistent physical explanation.

Such a conjecture allows an interpretation as to how the coronal rotation will be different depending on whether it is seen in white light or in the Fe XIV emission. For example, during the ascending phase of the activity cycle (1977–1979), the presence of active regions at high latitude dominated the Fe XIV signal at those latitudes and impressed the chromospheric signal on the overall rotation signature. The importance of this contribution lessened toward maximum and has declined, just as the level of activity declined, towards the succeeding minimum. We do not believe that the present study has either the precision or resolution to allow the inference of migration of the peak of this effect down toward the equator, as claimed by Antonucci and Svalgaard, but the data are consistent with the notion that this activity migrates toward the equator, as seen in the data for 1980 in Figure 8, in agreement with Antonucci and Svalgaard. When these regions exist at high latitude (very early ascending phase of the solar cycle), they heat the large-scale K-corona in a pattern which behaves with the rotation characteristics of the chromosphere.

Our conjecture is equivalent to viewing the overall Fe XIV signal as being a modification of the K-coronal signal by the

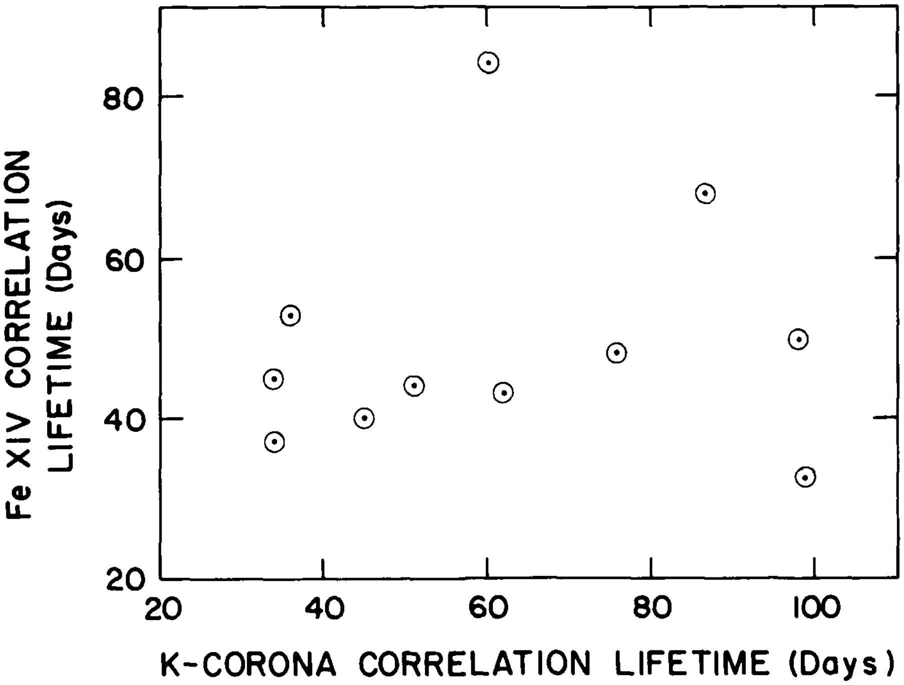

FIG. 10.—Comparison of coronal correlation lifetime identified from white-light and green line observations. Correlation lifetimes estimated by Fisher and Sime (1984a) from the K-coronameter data are plotted vs. those estimated from the Fe XIV data for the interval 1974–1985. These data are from the latitude band ±60°. There are no white-light observations for 1979.

distribution of local heating centers. The interaction of the overlying density structure with the local heating sources will lead to a pattern the details of which will depend on the relative sizes, and temporal and spatial scales of the two organizations. The drifting of a heating source of comparable scale through a coronal density structure will cause the correlation signal to be reduced in magnitude compared with that which would be found if the structures were at rest with respect to each other. As a result, the correlation, at say, one rotation lag will be reduced compared with the result for either individually.

More specifically, if the spatial scales are the same, and the rotation rates are the same (i.e., no relative motion), we expect to see the same signal as for the K-corona. Where slow relative motion does exist between the density and temperature structures, we expect the resulting rotation period to be equal to the slower period plus half the difference of the two underlying periods, and also that there will be some decorrelation (reduction of τ). When the scales are significantly different, but no relative motion is present, we expect to see the smaller scale; but when relative motion does become important, the lifetime would be reduced because of decorrelation. For structures of not greatly disparate scale sizes, the resulting period would be the mean of the two individual periods and the appropriate scale would be the smaller of the two.

These two effects, relative motion and the prevalence of the smaller scale, would therefore lead to the following situation. When large-scale density structures are present, and comparably stable local regions of heating exist, then, if these are of similar or smaller scale, the resulting brightness distribution will reflect the distribution of heating. If this displays a chromospheric character, then this will be impressed on the overall rotation signature. On the other hand, if the regions of heating are short-lived or of comparable lifetimes, and of a similar or smaller scale, then the rotation signal measured will have the characteristics of the coronal density distribution. Near the maximum of the solar cycle, we see the first case, with comparable lifetimes and a strong influence from the differential component of rotation which reduces lifetime estimates even more. Near solar minimum, the second case prevails. The observations reveal the same rate and rigidity signal as for the K-corona, but with reduced lifetime due to evolution, or to a slight relative motion of the density and heating distributions. Thus the interpretation of the Fe XIV signal as arising from the heating from local centers is qualitatively consistent with the observations.

These results concerning the behavior of the solar emission-line corona are of intrinsic interest since they contrast with the better documented properties of the coronal density structure. They are also of interest because it is by emission from (largely) collisionally excited plasma that we are able to detect coronae on other stars. The present data enable us to infer what might be seen from integrated light observations of a stellar corona, and to interpret that on the baseline of our knowledge of the Sun. In this case, the global average numbers indicated in Figure 2 suggest that we would be able to infer the presence of the corona and its slight response to the cyclic variation of the star beneath it. However, not much else is discernible. Although detailed characterization of the differential component of the rotation properties would not be possible, because the temporal modulation of the rotation rate appears to arise from the contribution of the high latitude zones, it would be possible to establish the existence, and perhaps an estimate, of the order of magnitude of such an effect. Exploitation of this data set for the interpretation of effects detectable in stellar observations is the subject of further study.

VI. SUMMARY

In summary, we have estimated the rotational behavior of the solar corona seen in the Fe XIV (5303 Å) line. The average rotation rate is very similar to that of the electron corona established from observations with the K-coronameters. There is little variation with time, and what is present (an increase of about $\frac{1}{2}$ day per period) has been observed in the years leading up to solar maximum, as was the case for the white-light corona. The modulation does not appear to be quite as deep as for the white-light corona, and it is difficult with data available to claim that it is cyclic, although the minimum observed rotation periods occur near solar minimum. In the average, the variation with latitude of the rotation period (Fig. 1) is similar to the K-coronal data: there is little average differential rotation. However, in contrast to the case for the electron corona, differential rotation is clearly identified in some years. These are the years before solar maximum, when the differential rotation with latitude has an amplitude of about half that exhibited by the photospheric tracers of rotation.

As with the white-light data, we have been able to estimate a persistence parameter for the Fe XIV signal, τ. The quantity had values comparable to, and somewhat lower than, the corresponding results for the K-corona. In contrast with the K-coronal results, there is little variation with time of this quantity for the Fe XIV data with the exception of the appearance of long-lived regions in 1984 and 1985. In spite of this difference between the Fe XIV and K-coronal results, the two sets of observations display a similar distribution in latitude of this quantity.

Comparison with previous observations has indicated that the general character of this data set is similar to that of the long term data series assembled by Antonucci and Svalgaard (1974). Many of the same features are demonstrated, but the onset of differential rotation and its association with developing solar photospheric and chromospheric activity appears to be different in detail in these observations with the present data showing strong differential rotation in the ascending and maximum phases of the solar activity cycle.

These observations have lead us to an interpretation of the Fe XIV signal as arising from a geometric superposition of locally heated regions on the large-scale coronal density structure. This is different in detail from the interpretation of earlier workers who took an interpretation based on distinct magnetic field structure sizes. Whereas the Fe XIV data here may be consistent with the scale size argument put forward by Fisher and Sime (1984) the measurements of persistence suggest that the thermal interpretation may be more appropriate. We thus infer the existence of two components which dominate the rotation signal at different times. In particular, the chromospheric or thermal component dominates high latitudes at and before solar maximum and appears to move equatorward beginning in 1979 or 1980, just before the maximum of the activity cycle. We identify this component with the high latitude activity described by Altrock (1988) and others.

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